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SENSITIVITY FACTORS FOR TYPHOON GENESIS OVER THE WESTERN NORTH PACIFIC DURING JULY-SEPTEMBER

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Abstract: The paper compares the correlations between individual factors of the cyclogenesis and the number of TCs formed in the western North Pacific in July to September (NTWNP). It also compares the characteristics of zonal anomaly distribution of the factors in the primary TC source areas of the Northern Hemisphere. Results show that the vorticity factor has the closest correlation with NTWNP. In TC genesis conditions, this feature is relatively rich but not enough, which determines that it is the sensitivity factor of NTWNP's annual variation. The paper also analyzes the source of annual variation of the vorticity factor in the key area of the western North Pacific as well as its advantage in showing NTWNP. Results show that the annual variation of the vorticity factor mentioned above is related to the annual variation of Southern Oscillation, Antarctica Oscillation and the geopotential height field of East Australia, which reflects the effect of two large-scale systems in the Southern Hemisphere and ENSO (El Niño–Southern Oscillation) on NTWNP. Since the area where the vorticity factor is significantly correlated with NTWNP is consistent with the area of dense TC genesis sources, the vorticity factor has an obvious advantage in showing annual variation of TCs. Those features are very significant for research on the influencing mechanism of NTWNP and simulation of climate models.

Key words: statistical characteristics; contrastive analysis; vorticity factor; sensitivity

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1 INTRODUCTION

The tropical cyclone (TC) is one of the serious natural disasters. Along with the development of social economy, the requirements for prediction of monthly and seasonal variation of the TC are increasingly higher. Prediction of the number of TCs is the most primary and important part in prediction of TC-related disasters. Through research and review of the TC activities over the western North Pacific on the seasonal, annual and interdecadal scales, Chen and Huang[1] indicated that the main systems influencing the variation of TC activities in different time scales include low-frequency oscillation[2], monsoon trough[3], west-propagating equatorial waves[4], ENSO[5, 6] and QBO phenomena[7]. These systems can change the atmospheric circulation over the western North Pacific, thus affecting the variation of the TC activities over the western North Pacific on different time scales. Moreover, they have conducted a detailed research on the effect of thermal states of the warm pool in the western North Pacific on those activities. Results showed that the subsurface sea temperature of the warm pool is significantly correlated with the number of TCs[8]. In the opinion of Lin and Zhang[9], the sea surface temperatures of the warm pool in the western North Pacific (120−150°E, 10−20°N) and the sea area of equatorial central-eastern Pacific (180−90°W, 10°S−5°N) have a close correlation with the TC activities from January to June. The former is positively correlated while the latter is negatively correlated. The research conducted by Zhang and Qian[10] showed that the South Asia High also has a certain effect on the frequency of TCs.

There are many factors in the environmental background field that have an effect on TC genesis, but its eventual determinants are its source's ocean-surface thermal state, near-surface-layer vorticity and wind shear between the higher and lower layers, as well as the instability and humidity of the static force in the lower troposphere. In 1975, Gray proposed a set of standards (see Royel et al.[11]), which represents the geographical distribution of

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seasonal occurrence frequency of the TCs in the climate conditions at that time, which is called SGP (Seasonal Genesis Parameter) and also known as the Gray index, determined on the basis of three thermodynamic variables (marine thermal energy, relative humidity and moist static stability of the lower atmospheric layer) and three dynamic variables (Coriolis effect, vertical wind shear and lower-layer relative vorticity). These variables are all calculated from the seasonal averages of large-scale fields (see section 2). The sum of the four SGPs is YGP (Yearly Genesis Parameter). Watterson et al.[12] have attempted to introduce SGP into the analysis of seasonal variation and yearly variation of the TC genesis number. In their opinion, although this index was developed to study the climate field, it should also have the potential function of showing the direct effect of large-scale atmospheric circulation and thermodynamic abnormity on TCs in a single season. Their research results show that the TC genesis number represented by their simulated SGP has an appropriate correlation with the number of TCs observed over the Central Pacific, eastern North Pacific and North Atlantic. Unfortunately, it does not have a significant correlation with other oceans, including the western North Pacific.

As we know, the six physical variables to calculate the SGP are indeed the most primary variables that have a significant effect on the formation of a TC. The cause for the variance described above may be that each variable contributes differently in different parts of the sea. In a specific area, some variables may contribute much more than the others. Thorncroft and Ioannis[13] indicated in their research that the TC activities over the Atlantic have a close negative correlation with the wind shear in the main development areas of TCs from July to September.

Then, how much does each variable in SGP contribute to NTWNP? Which is/are the main factor(s)? By comparing each factor in SGP for the TCs over the western North Pacific, we will know the sensitivity factor of NTWNP, thus having a deeper insight into the possible mechanism of NTWNP and improving the predictability of climate models on NTWNP.

The rest of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 compares each of the seasonal TC genesis parameters. Sources of annual variation of the vorticity factor are given in section 4 and advantages of the vorticity factor in showing the variation of NTWNP are given in section 5. Section 6 summarizes the main findings.

2 DATA AND METHODS

Because each of the datasets collected after 1968 covers almost the same TC data and is in good consistence[14], the period from 1968 to 2006 is taken for analysis. The data to be used includes the sea temperature data from JEDAC (Joint Environmental Data Analysis Center), the reanalysis data from NCEP (National Centers for Environmental Prediction) and the best track data from JTWC (Joint Typhoon Warning Center). The intensity of each TC mentioned in this paper is at a higher level than a tropical storm (greater than or equal to 35 nautical miles per hour). The season for analysis is summer (from July to September). Summer is the season with the highest TC occurrence frequency and the number of TCs occurring in summer accounts for 54% of the yearly total number. Since the variation of an influencing factor in different seasons may lead to the variation of the sensitivity factors, only summer is taken as the object for research.

Gray's SGP of TC[11] is defined as the following formula:

$$SGP = (|f| \times I_\zeta \times I_S) \times (E \times I_\theta \times I_{RH})$$

The first three items are dynamic items, which are described respectively as follows:

$f=2\Omega\sin\varphi$ represents the parameter of Coriolis effect (φ represents the latitude and Ω represents the earth angle) with a unit of $10^{-5}s^{-1}$. Since this factor is only related to the latitude rather than the number of TCs, it is not analyzed in this paper.

$I_\zeta = (\zeta_r \frac{f}{|f|}) + 5$, in which ζ_r, with a unit of $10^{-6}s^{-1}$, represents the relative vorticity (vorticity factor) at the lower layer with a pressure of 925 hPa.

$Is = (|\frac{\partial V}{\partial P}| + 3)^{-1}$ represents the reciprocal of vertical shear of the horizontal wind between the 200-hPa and 925-hPa layers (wind shear factor), with a unit of m/s/725 hPa.

The last three terms are for the thermodynamics, which are described respectively as follows:

$E = \int_0^{60} \rho_w c_w (T - 26) dz$ represents the measured value of marine thermal energy (factor of marine thermal energy), which is defined as the integral of the remainder after subtraction of the sea temperature, i.e., 26°C, from the sea surface to the depth of 60 m, with a unit of 10^3cal/cm^2 (T is the temperature at the depth of z, and ρ_w and c_w are the density and thermal capacity of sea water respectively, which all can be regarded as constants).

$I_\theta = (\frac{\delta \theta e}{\delta P} + 5)$ represents the moist static stability (factor of moist static stability), which is defined as the vertical gradient of the equivalent potential temperature, θ_e, between the 500-hPa and 1000-hPa layers, with a unit of K/(500 hPa).

$I_{RH} = Max(\frac{RH-40}{30},1)$, in which RH represents the average relative humidity between the 500-hPa and 700-hPa layers. As this index is basically a homogeneous field, this paper does not analyze it.

3 COMPARISION OF INDIVIDUAL FACTORS OF SEASONAL TYPHOON GENESIS

3.1 *Comparison of correlations between individual factors and NTWNP*

First, we compared the correlations between each of the factors and NTWNP, i.e., the number of TCs occurring over the western North Pacific in summer, and the results are shown in Fig. 1. All the factors, except the vorticity factor, have a weak correlation with NTWNP. This is why the test conducted by Watterson et al.[12] for the western North Pacific failed, and also why it is hard to predict the TC occurrence frequency during the period from July to September. As shown in the comparison, vorticity is the key factor that has a significant effect on NTWNP. The area where the vorticity is significantly correlated with NTWNP is mainly the region (17.5−27.5°N, 130−160°E) in the western North Pacific, called the key area. It is positively correlated with NTWNP, i.e., when the vorticity of the key area has a positive (negative) anomaly, NTWNP is more (less) correspondingly. Remarkably, the correlations of the individual factors with the number of TCs occurring over the western North Pacific in a whole year are quite different from their correlations with NTWNP as described above. Other than the vorticity that still has a close correlation with the annual number of TCs, other factors all have an area where they are significantly correlated with this number (figure omitted). Among them, the factor of marine thermal energy is especially so, which has a close negative correlation with the annual number in the western and northern parts of the area south of 30°N and west of 170°E.

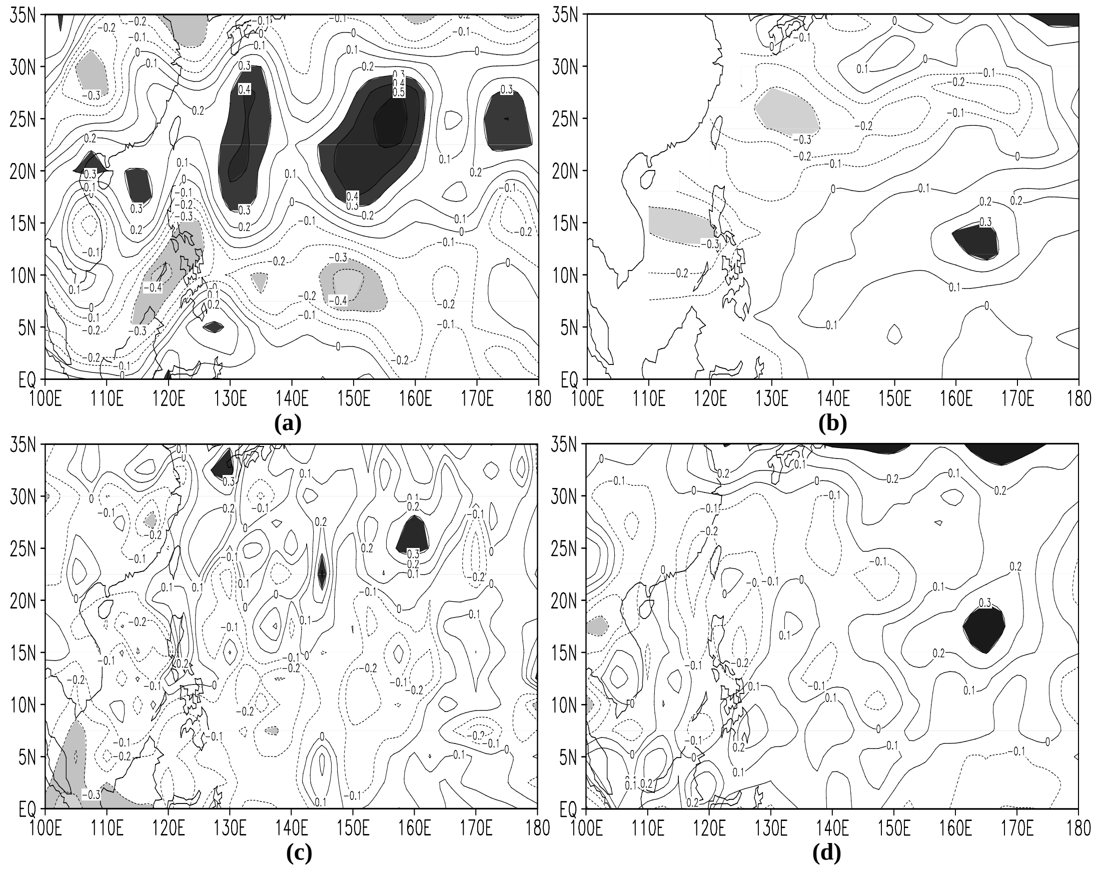


Figure 1. Correlations between individual factors and WNPSTYN. The shaded areas pass the significance test with a reliability of 95%. a. vorticity; b. thermal sea power; c. wind shear; d. moist static instability.

In order to have an insight into the capacity of key-area vorticity in showing NTWNP, we have conducted an analysis on the sequences of the average annual vorticity indexes in the key area and the average annual numbers of TCs generated over the western North Pacific in summer during the period from 1968 to 2006. Results show that the two sequences have a good consistency in annual variation. Their correlation coefficient is 0.53, which can pass the correction significance test with a reliability of

99%. This consistency is even higher in the periods before 1983 and after 1994; it is lower in the period from 1984 to 1993.

3.2 *The important position of vorticity factor in seasonal typhoon genesis parameter of the western North Pacific*

Gray’s seasonal TC genesis parameter is a complex index, i.e., the product of each of the factor indexes. In order to compare a complex factor and a single factor’s correlations with NTWNP, we conducted an analysis on the correlations with NTWNP for two complex factors, vorticity-wind shear and vorticity-wind shear-marine thermal energy-moist static instability (Fig. 2). As is shown in the figure, the distribution of the correlation between the complex factor of vorticity-wind shear and NTWNP in summer is very similar to that of the correlation between the vorticity and NTWNP, whether as a whole or in a single significant-correlation area. For the complex factor determined with the product of the four factors, i.e., vorticity, wind shear, marine thermal energy and moist static instability, the distribution of its correlation with NTWNP is also consistent with the correlation between the vorticity and NTWNP as a whole, but to a lesser extent. The correlations between other complex factors and NTWNP are all weaker than the two described above. The distribution of the correlation between the vorticity-involved complex factor and NTWNP is consistent with that of the correlation between a single vorticity factor and NTWNP, further proving that the vorticity is the key factor affecting NTWNP.

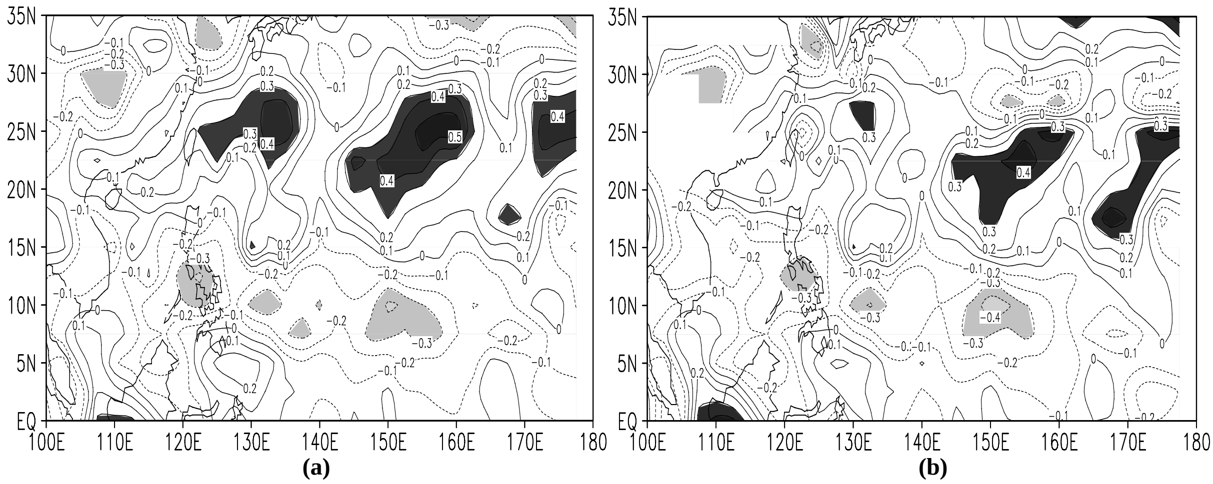


Figure 2. Correlations between complex factors and WNPSTYN. a. vorticity-wind shear; b. vorticity-wind shear-marine thermal energy-moist static instability.

In order to further prove the important position of the vorticity factor in the TC genesis in the western North Pacific, we compared the climatological states of each factor for the primary TC genesis sources in the Northern Hemisphere (the low-latitude regions of the western North Pacific, central-eastern Pacific and North Atlantic). Moreover, we analyzed the average values of each factor during the period from 1968 to 2006 to calculate the zonal average values, and the zonal anomaly distribution of each factor is shown in Fig. 3. As is shown in the figure, the vorticity index of the western North Pacific is slightly greater than the central-eastern Pacific and much greater than the North Atlantic (Fig. 3a). The vorticity index is less than −10 in most areas of the North Atlantic, and basically ranges from −10 to 0 in the central-eastern Pacific; for the western North Pacific, it is slightly less than 0 to the east of 150°E, greater than 0 to the west of 150°E, and even greater than 10 in the area of South China Sea. The zonal anomaly distribution of wind shear index is contrary to the distribution of vorticity index, and the wind shear index of the Atlantic is much greater than the western North Pacific and central-eastern Pacific (Fig. 3c). The anomaly of the wind shear index is greater than 0 in the Atlantic TC source areas, less than 0 in the central-eastern Pacific, and around 0 in the western North Pacific. With regard to the anomaly of marine thermal energy index and moist static instability index, the Northern West Pacific and North Atlantic both have a similarly positive anomaly distribution (Fig. 3b and 3d), but the central-eastern Pacific has a negative anomaly distribution. In the vertical circulation of tropical atmosphere, the central-western Pacific is a depressed area, and its sea water is colder comparing to the area at the same latitudes. Hence, the moist static stability and marine thermal energy (thermodynamic factors) have a significant effect on TC genesis in this area, and climate warming leads to a much greater number of TCs[15]. With regard to TC genesis in the western North Pacific and North Atlantic, the requirements for moist static stability and marine thermal energy are both met, and the thermodynamic factors have a much weaker effect on the number of TCs while the dynamic factors dominate. As indicated in Chiris and Ioannis[13], NTWNP has the closest correlation with the wind shear, which is corresponding to the positive anomaly area of wind shear index in the North Atlantic (greater than that of the western North Pacific). However, in Fig. 3a, the vorticity index of the western North Pacific is greater than that of the North Atlantic. The vorticity factor for the western North Pacific is just like the wind shear factor for the North Atlantic, which is relatively rich but not enough. It is this feature that makes the vorticity factor become the key factor affecting NTWNP.

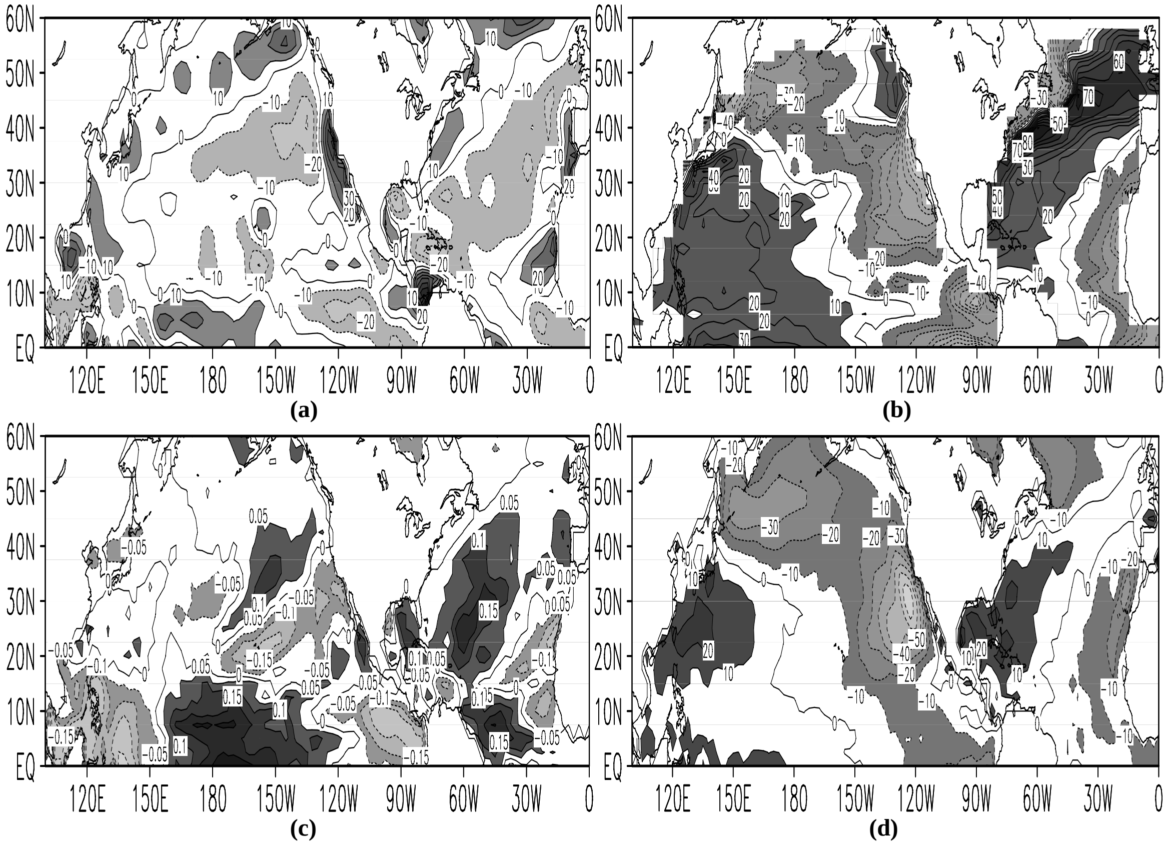
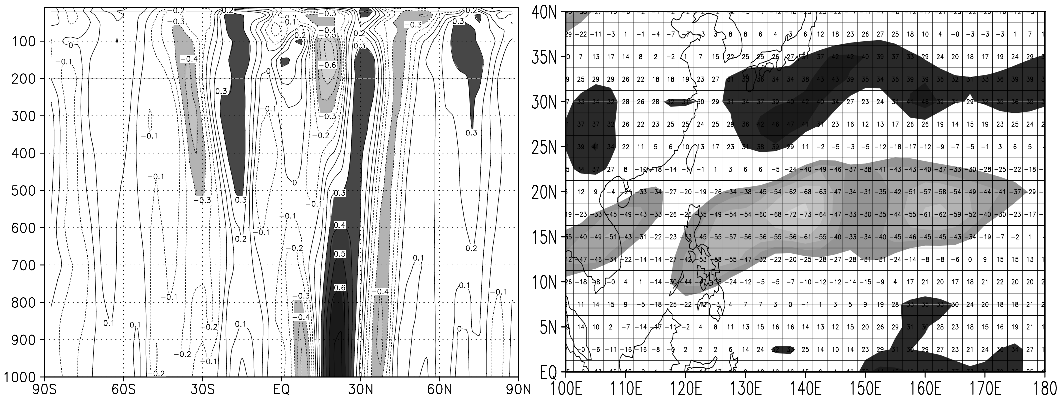


Figure 3. Zonal anomaly fields of individual factors in the range from 100°E to 0°. a. vorticity; b. marine thermal energy; c. wind shear; d. moist static instability.

4 SOURCE OF ANNUAL VARIATION OF VORTICITY FACTOR

As described above, NTWNP is significantly correlated with the vorticity in the layer of 925 hPa above the key area (17.5−27.5°N, 130−160°E). Then, what leads to the annual variation of the vorticity in the key area? Where is the source of annual variation of the vorticity in the key area? In order to answer these questions, we conducted an analysis on the vorticity field. The zonal distribution of the correlation in each layer between the average vorticity in the key area and the average vorticity in the area with the same longitudes (130−160°E) is shown in Fig. 4a, and the distribution of its correlation with the vorticity in the layer of 200 hPa is shown in Fig. 4b. As shown in the figure, in the middle and lower layers (below the layer of 500 hPa), the correlation with the key area becomes less significant at a further location, except on the two sides where there exist significantly correlated areas. Hence, we are convinced that the source does not move from the middle and lower layers to the key area. The source of vorticity variation is more likely the upper layers. In Fig. 4b, the significant negative correlation between the upper troposphere and key area supports this opinion. Moreover, at the upper troposphere, there is also a significantly correlated area at another location above the key area. This means the source may transfer abnormity from the current layer to the upper troposphere above the key area, which will lead to the variation of the vorticity in the key area, thus affecting the TC occurrence frequency of the western North Pacific. As shown in the figure, the correlation in the Southern Hemisphere is more significant than in the Northern Hemisphere, which means the source of annual vorticity variation may be the Southern Hemisphere. As indicated in Li[16] and Xu and Wu[17], the cold air activities in the Southern Hemisphere have a significant effect on NTWNP, which supports the arguments described above to a certain extent.



(a) (b)

Figure 4. a. Longitudinal distribution of the correlation in individual layers between the average vorticity in the 925-hPa key area (130-160°E, 17.5-27.5°N) and the average vorticity in the area with the same longitudes; b. distribution of the correlation between the average vorticity in the key area and the vorticity in the layer of 200 hPa (the gridpoint data is obtained by multiplying the coefficients of correlation by 100).

In order to further explore the source of annual variation of the vorticity factor, we select a key area (140−165°E, 15−22.5°N) in the layer of 200 hPa (Fig. 4b) to determine the distribution of the correlation between its average vorticity and the vorticity field of 200 hPa (Fig. 5). As shown in the figure, there is an area with a significant positive/negative correlation with the key area in terms of average vorticity, which lies to the south/north of 30°S and between 150°E and 170°W over East Australia. This is consistent with the statement above that there exists a significant positive/negative correlation area in the Southern Hemisphere far from the key area. The significantly correlated area of East Australia is also important for the annual vorticity variation in the upper layers over the western North Pacific, which plays an important role in determining the NTWNP. Besides, the tropical East Pacific also has significant areas with their correlation coefficients slightly lower than those of East Australia, which includes a negative correlation area in the equatorial East Pacific and a positive area to the south of the negative one. Remarkably, the positive area to the south of the tropical East Pacific is exactly located over Easter Island (109°30′W, 29°00′S), corresponding to the one over Darwin (130°59′E, 12°20′S) in East Australia. Hence, the further correlated area over the tropical East Pacific can be linked with the one over East Australia through Southern Oscillation to make a combined effect on the vorticity variation of the western North Pacific, thus affecting NTWNP. In addition, there is another significant correlation area (weaker than East Australia) over the region (130°W, 60°S), which, together with the one over East Australia extending to the central South Pacific, forms a train of positive and negative waves in turn that extends from high latitudes to low latitudes. Similarly, Wang and Fan[18] used a train of waves at the 200-hPa upper troposphere to explain the mechanism of Southern Oscillation affecting NTWNP. Meanwhile, we also analyzed the correlation between the average vorticity in the key area of 200 hPa and the geopotential height field (figure omitted). Results show that there is a negative correlation area in the layer of 500 hPa over East Australia while there is a positive one over the western North Pacific. This distribution is consistent with an analysis conducted by Sun et al.[19] on the spatial distribution of the correlation between the time series of the average 500-hPa geopotential height field to the east of Australia (25−35°S, 150−170°E) in summer (from July to September) and the one in the same layer during the same period. As indicated in the research, the abnormity of circulation to the east of Australia has a close correlation with the frequency of TC activities over the western North Pacific. The analysis above shows that the annual variation of the vorticity factor that affects the variation of TC occurrence frequency of the western North Pacific is caused by ENSO, circulation abnormity to the east of Australia in the Southern Hemisphere, or the Antarctica Oscillation.

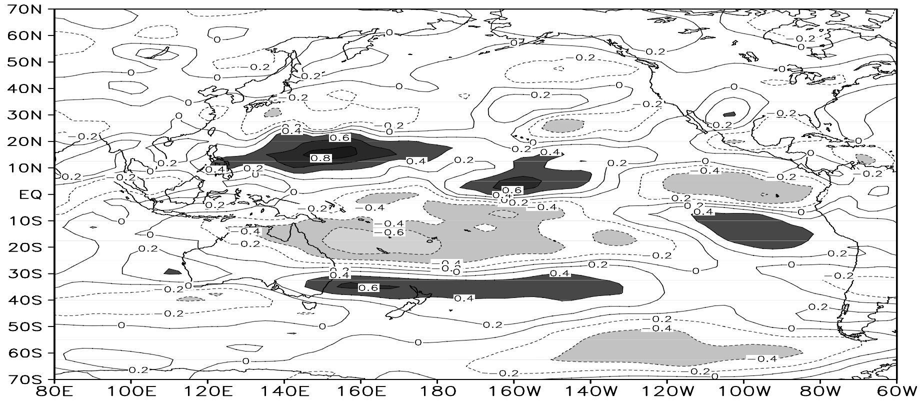


Figure 5. Distribution of the correlation between the vorticity in the layer of 200 hPa and the average vorticity in the key area (140-165°E, 15-22.5°N).

5 ADVANTAGE OF VORTICITY FACTOR IN SHOWING NTWNP'S VARIATION

What is the advantage of vorticity factor for showing the variation of NTWNP? As is shown in the study, the tropical zonal wind shear between the higher and lower layers has a significant correlation with NTWNP. He et al.[20] defined the difference (ΔU200−ΔU850) between the two areas significantly correlated with each other, i.e., the equatorial central-eastern Pacific (135−82°W, 7.5°S−7.5°N) and tropical West Pacific (102.5°E−170°W, 2.5−17.5°N), as the index of zonal wind shear between the higher and lower layers over the tropical Pacific. The index of zonal wind shear between the higher and lower layers over the tropical Pacific in the active season of TCs has a positive correlation with the number of TCs generated over the western North Pacific, and the coefficient of correlation is 0.63, at a higher level of significance than 0.001. As mentioned above, the coefficient of correlation between the average vorticity in the lower-layer key area and NTWNP is 0.53, slightly less than the index of zonal wind shear. In spite of that, if we select a significant correlation area in a high layer (say, 100 hPa) as the key area, the coefficient of correlation between its average vorticity and NTWNP can reach −0.62, comparable with the index of wind shear.

Although the significant correlation between the tropical zonal wind shear and NTWNP is similar with the vorticity factor, its physical meaning is unclear. Even though the Walker circulation is used to explain it, its physical meaning is still unclear. The main cause is that in the analysis, the Walker circulation and the wind shear itself both lie in the tropical area to the south of 17.5°N, but the main source region of summer TC genesis, with 17.5°N as its central axis, concentrates in the area (10−25°N, 120−150°E), as shown in Fig. 6. Fig. 6 is composed of the scatter diagram of summer TC genesis sources and the distribution maps of annual increments[21] of correlations of NTWNP with the zonal wind shear between the higher and lower layers (Fig. 6a), the vorticity in the layer of 200 hPa (Fig. 6b), and the vorticity in the layer of 925 hPa (Fig. 6c). As shown in Fig. 6a, the dense area of TC genesis sources does not match with the significant (negative) correlation area of the zonal wind shear between the higher and lower layers. Besides, there is also a positive area significantly correlated with NTWNP, which is a quite large number in this area. Different from the factor of zonal wind shear, the vorticity factor has a significant correlation area that is basically consistent with the dense area of TC genesis sources, especially in a lower layer (Fig. 6c). Inconsistency between the significant correlation area and the dense area of sources means that the factor of zonal wind shear is not a direct factor affecting TC genesis, and its effect is indirect, just like an additional correlated area. As shown by the comparison of each factor in SGPI above, the vorticity factor's effect on NTWNP has a clear physical meaning. The vorticity not only affects the genesis of a single TC, but also determines the variation of the number of TCs generated over the western North Pacific in terms of season. Remarkably, when the annual increment is used to analyze the correlation of annual variation, the higher-layer vorticity (Fig. 6b) has a more significant correlation with the number of TCs than the zonal wind shear that is only comparable with the lower-layer vorticity. In fact, the factor of zonal wind shear has an internal relation to the vorticity factor. The zonal wind shear between the higher and lower layers reflects the difference between the higher-layer and lower-layer winds, and the vorticity reflects the meridional shear of zonal wind and the zonal shear of meridional wind, especially the former. As indicated in the analysis, the higher-layer vorticity and lower-layer vorticity both have a negative correlation with the number of TCs. When the vorticity shear is taken for analysis, it not only includes the vertical shear of zonal wind, but also takes into account the meridional shear of this vertical shear.

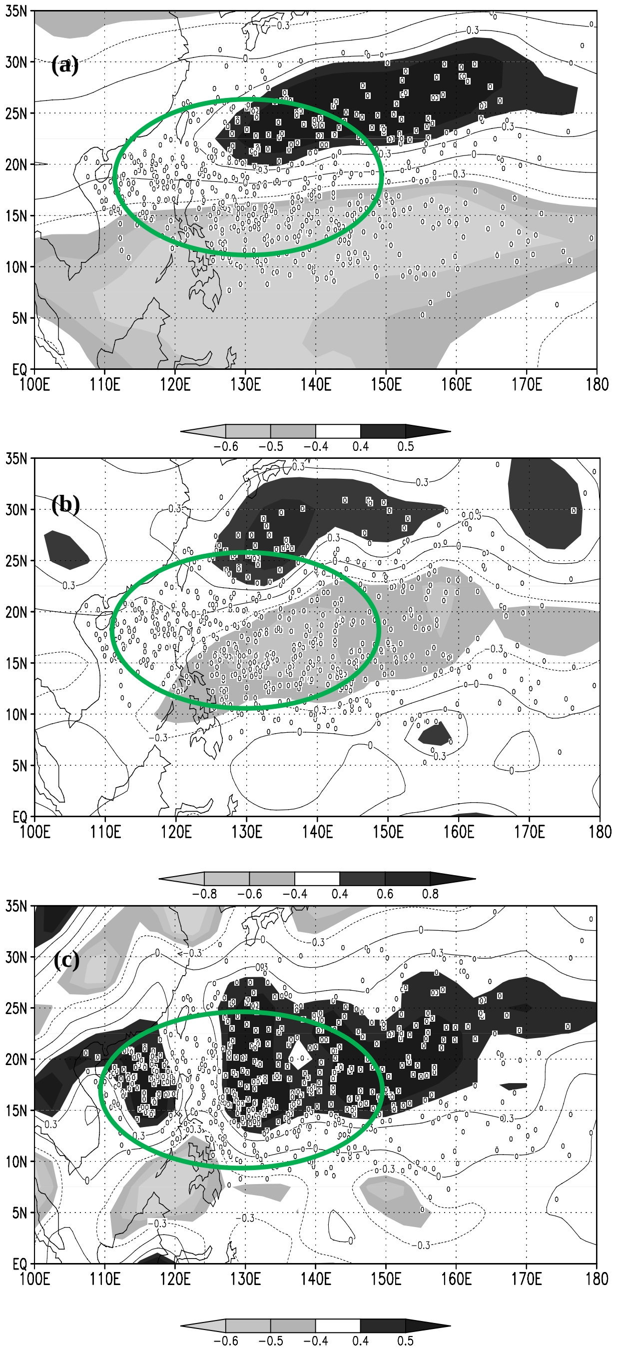


Figure 6. Scatter diagram of summer typhoon genesis sources (dots) in the western North Pacific and distribution maps of annual-increment correlations of WNPSTYN with the zonal wind shear between the higher and lower layers (a), the vorticity in the higher layer of 200 hPa (b), and the vorticity in the lower layer of 925 hPa (c), during the period from 1968 to 2006.

As indicated by the comparative analysis above, the vorticity factor has an obvious advantage in showing NTWNP. The significance of its correlation with NTWNP is similar with the wind shear between the higher and lower layers, a factor that has a significant correlation with NTWNP. Moreover, it also has a direct effect on NTWNP, which has a clear physical meaning.

6 CONCLUSIONS

This paper compares the correlations between each factor of the TC genesis and NTWNP, as well as the characteristics of zonal anomaly distribution of each factor in the Northern Hemisphere's main TC source areas. Moreover, it also analyzes the source of annual variation of the vorticity factor in the key area and its advantage in showing NTWNP's variation.

(1) Compared with other factors of the TC genesis, the vorticity factor has the closest correlation with NTWNP.

(2) The complex factor composed of the vorticity factor and other factors has a weaker correlation with NTWNP than the single vorticity factor.

(3) As indicated by the zonal comparison of each factor in the main TC source areas of the Northern Hemisphere, the vorticity factor in the western North Pacific prevails.

(4) The source of annual variation of the vorticity factor is in the Southern Hemisphere, which is related to the cold air activities of Australia, Antarctica Oscillation and Southern Oscillation.

(5) The vorticity factor's effect on NTWNP has a clear physical meaning, and the area where the vorticity factor is significantly correlated with NTWNP is consistent with the dense area of TC genesis sources. Hence, it has an obvious advantage in showing NTWNP.

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